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Sustainable Non-destructive Technique Ambient Vibrations for Ground Assessments

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Abstract

Sustainable approach, cost-effective, precise and reliable outcomes become a great challenge in monitoring or re-evaluating the existing site-structure especially with minimum engineering database. Simple, fast, cheap, non-destructive, minimum handling operator and reliable findings of ambient vibration testing (AVT) and Horizontal to Vertical Spectral Ratio (HVSR) method has proven successful in site dynamic characteristics assessments of SK Sri Molek situated in Batu Pahat district, Johor, Malaysia. Although many expectations believed the survival of existing low-rise building is higher under earthquake threat, but moderate resonance effect was classified at similar study area from previous investigation. Determination of site fundamental frequency, F_o may assist further evaluation in seismic hazard assessments, ground condition monitoring as well as local soil characterization. The F_o were obtained from 2.05 to 4.07 Hz from the microzonation map produced with good verification presented between AVT outputs against two bore log records, for ground classification and sediment thickness predictions of sedimentary covers.

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Keywords: Sustainable approach; ambient vibrations testing; HVSR method; site fundamental frequency

1. Introduction

Rapid constructions from rural to urban area in developing country such as Malaysia have created a new era and challenge in many sustainability issues. In design and construction industries, structural integrity must be assured for

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an engineering design to be functioned and withstand along service life from structural failure which could give threats to safety and loss of asset. Regular monitoring or specific re-evaluation programme may reduce the risk and update the health condition of existing site-structure. Any improvement or strengthening strategies to maintain and lengthen operational lifespan of existing structure must be well planned before remedial action is taken.

Recently, East and West Malaysia have experienced frequent earthquake tremors from neighboring region of Sumatra fault zones and low intensity earthquakes from local faults as well. Many structural damages were reported among engineered low rise reinforced concrete buildings mostly in the felt tremor zones. The attention on ground and structural damages assessment and hazard mitigation has attracted many researchers to survive the existing structures to reduce the risk. The advantages of AVT and HVSR method for no to high seismicity region in assessing dynamic characteristics such as of natural frequency, F_o has created a great chance to fulfill sustainability issues. It can be carried out in a passive seismic method without user-generated seismic energy, and can be relied on measurement of ambient noise sources (Haefner, Sheets, & Andrews, 2010). The onsite methodology of ambient vibration testing is rather simple, cheap, quick, smaller number of operators needed, non-destructive even enable to produce reliable prediction with minimum engineering database that could be due to poor managing record system or the structure itself is too old.

The HVSR method was originally proposed by Nogoshi & Igarashi (1971) and wide-spread by Nakamura (1989). HVSR is derived from the ratio of Fourier amplitude spectral of horizontal components to vertical component, which transformed from the seismic wave field such as microtremor records (also known as ambient vibration or ambient noise). Kanai &Tanaka (1954, 1961) in Beroya, Aydin, Tilgo & Lasala (2009) were the first to propose a method to classify the ground conditions based on the characteristics of noise spectra where they suggested the period distributions curve of microtremors shows a definite form for each subsoil type. Application of natural frequency in sediment thickness prediction, classification of soil strength and its characterizations, ground vulnerability assessment and site-structure resonance effect have been described in many studies (Motamed, Ghalandarzadeh, Tawhata & Tabatabaei, 2007; Dinesh, Nair, Prasad, Nakkeeran & Radhakrishna, 2010; Soemitro, Warnana, Utama & Asmaranto, 2011; Rahimi, Nikoudel, Moghaddas & Ghayamghamian, 2012; Kamarudin, Daud, Ibrahim, Z., Ibrahim, A. & Koh, 2014).

The function of school is not only for educational institution but also utilized as an assembly area for community including temporary shelter for natural hazard victims. Appropriate monitoring or re-evaluation mechanism without much destruction should be engaged to secure the integrity of the existing structure and stability of ground condition. Dynamic characteristics and seismic vulnerability assessment of primary school RC building of SK Sri Molek has shown to successful prediction by using integration methods of mictrotremor technique, standard codes of practices and some previous empirical equations (Kamarudin, Daud, Ibrahim, A & Ibrahim, Z, 2014). In similar study, resonance potential of site-structure is expected to be classified in moderate level that could be occurred under equal oscillation between building and ground frequencies, under strong ground shaking and may lead to structural damages.

Integration of geophysical method (such as AVT) with suitable empirical relationships from previous studies and standard design code of practices may give bigger perspective in re-evaluation of dynamic characteristics and seismic vulnerability assessment of existing structure (Kamarudin, Daud, Ibrahim, A & Ibrahim, Z, 2014). In this study, a sustainable feature from AVT and HVSR method has been utilized to evaluate the site fundamental frequency, F_o in a primary school compound of SK Sri Molek. By optimizing the characteristics of HVSR spectral curves and F_o values, the reliability of this approach have been verified against geotechnical data of bore log records for sediment thickness and ground classification predictions. Finally, the distribution of site fundamental frequencies is presented in form of microzonation map to illustrate sedimentary covers and ground classification of the study area.

2. Microtremor instrument, fieldwork, processing parameters and verification procedures

The instrument involved in this study comprises of 3 units Lennartz portable tri-axial seismometer of 1 Hz eigenfrequency sensors (S) and 400 V/m/s output voltage, CityShark II data logger, and 1 GB memory flash card data storage (see Fig. 1). Three seismometers are placed, levelled and aligned to the True North direction. The sensors are connected by geophone reinforced cable to the data logger, powered by internal 12 volts direct current.

During the ambient vibrations recording, the time series are measured in three major components of NS (North-South), EW (East-West) and vertical (V). All signals are stored in the flash card and transferred manually to the notebook.

Prior to the field microtremor measurement, all type of external noise disturbances such as extreme weather (strong wind, lightning, heavy rain etc.), transient noises (traffic, pedestrian, etc.), monochromatic sources (machinery, pumps, generator etc.) and nearby structures (tress, pipes, sewer lids etc.) should be avoided for good signal quality, accuracy and enough windows to predict natural frequencies of ground, as recommended by the European research project SESAME (2004).

Fig. 2(a) shows the location of study area which is located in the Southern part of Peninsular Malaysia (West Malaysia) or known as Johor. The study area is situated in Batu Pahat district that mainly concentrated by various employment sectors such as industry, business and service, public institution and educational, agricultural etc. with high population (see Figure 2(b) and Figure 2(c)). 28 grid points of seismometer sensors were assigned with the site photographs taken as in respective measurement lines given in Figure 2(d) and Figure 2(e). Three measurements were taken for every line when S1 was acting as reference sensor which placed at the center and the rest sensors were freely moved at both ends. 25 meter spacing was measured between grid points in each measurement line. Less structure obstacles found in the measurement area contributes to easy accessibility during fieldwork. For data logger setup procedure, 100 Hz of sampling rate was taken at optimum gain level within 15 minutes of recording length.

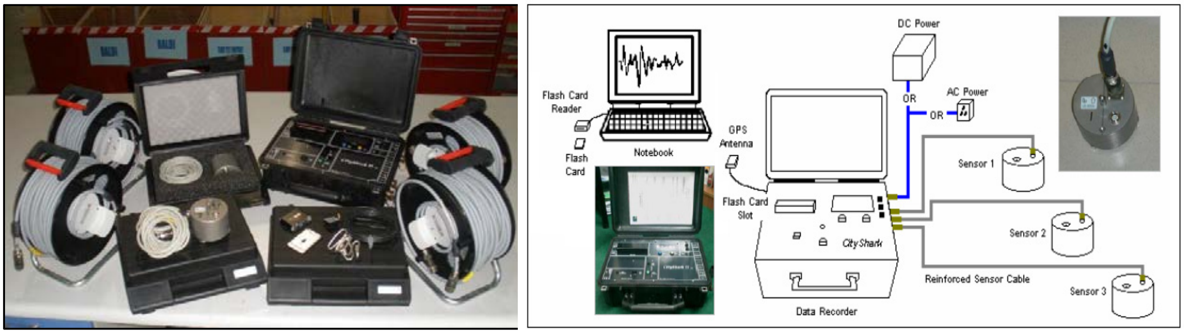

Fig. 1. Seismometer instrument and connections

Ambient vibration waves were processed using open-source software of GEOPSY for the peak frequency picking from the squared average HVSR curve. Fourier amplitude spectral transformed from three components of ambient vibration waves, then computed into HVSR as simplified in equation (1). The transforming processes involved several steps such as signal corrections, sampling window selections, signal filtering, transformation of Fourier amplitude spectra followed by computational of HVSR curves, spectral curves smoothing, calculation of mean and standard deviation of the HVSR (Pando, Cano, Suarez, Ritta & Montejo, 2008). 15-sec of automatic window length selection with anti-triggering algorithm and cosine taper of 5% were used. Smoothing constant of 40 by Konno Ohmachi was computed for each window length up to 16 Hz of frequency sampling. Details fieldwork and processing protocols can be found in the SESAME (2004) guideline. Finally, the identified fundamental resonant frequencies (peak frequency at the maximum amplitude) from every grid point were mapped into plane and three dimensional contour graphs or known as microzonation map.

$$\mathrm{HVSR} = \sqrt{\frac{H^2_{N\text{-}S} + H^2_{E\text{-}W}}{2V^2}} \tag{1}$$

Where,

$H_{N\text{-}S}$: Fourier amplitude spectra in the North-South direction
$H_{E\text{-}W}$: Fourier amplitude spectra in the East-West direction
V : Fourier amplitude spectra in the vertical direction

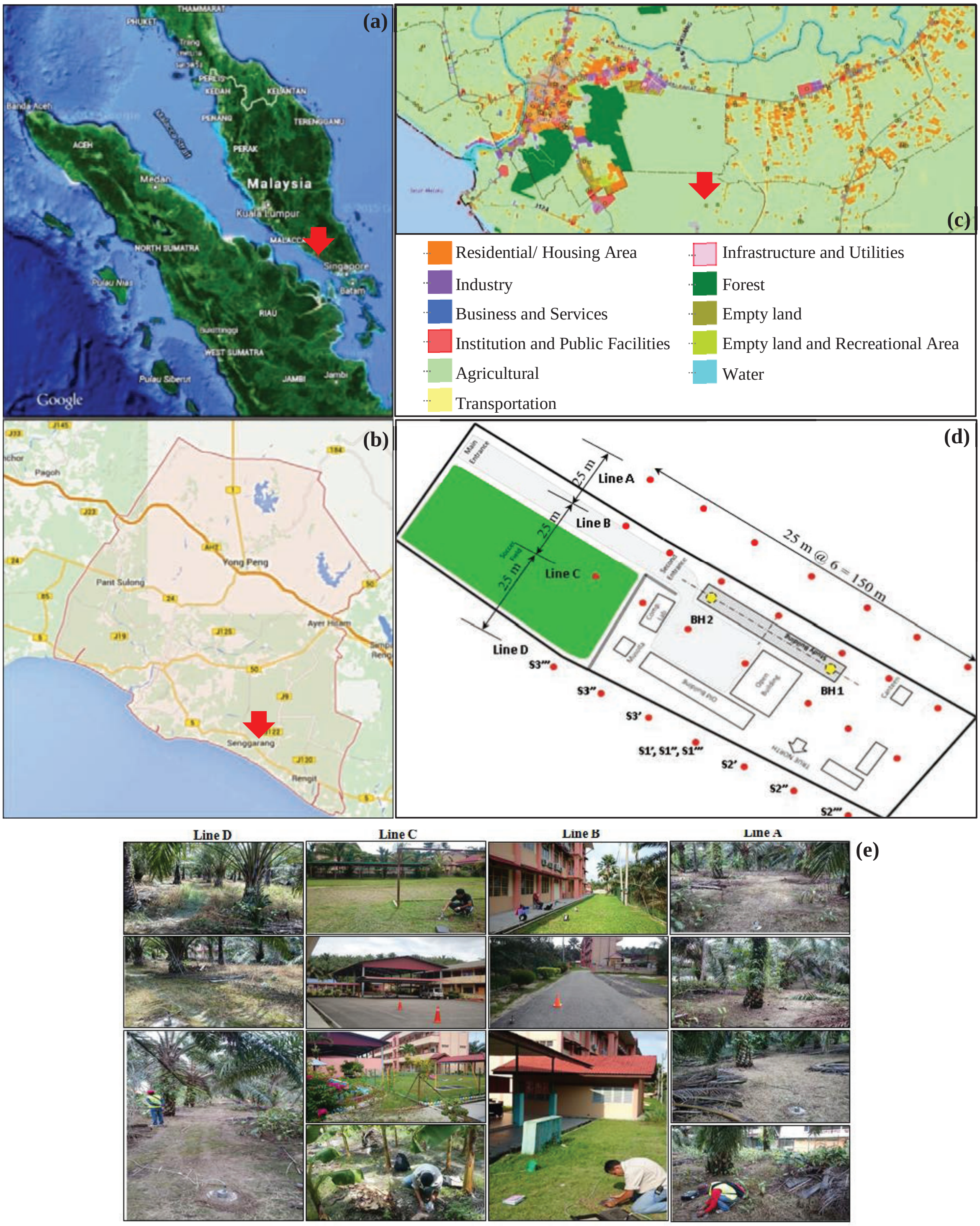

Fig. 2. (a) Pinned point of study area, (b) Batu Pahat district map, (c) Geographic Information System (GIS) of surrounding area from SK Sri Molek, (d) orientation of measurement lines and seismometer positions and, (e) fieldwork photographs

The subsurface profile, soil depth and standard penetration test blow count (SPT 'N') were extracted from the soil investigation report (SI) which has been collected from IKRAM group. In order to estimate the sedimentary cover by using an empirical formula formed in frequency function taken from previous study, the datum of soil depth must be determined according to the soil classification which can be referred from the SI and Table 2. Then, verification of the estimated soil thickness against the actual soil depth from two boreholes (BH) was made from the measurement points of S2' and S3'/ B and C, which the closest to these BH locations. The percentage of difference and relative deviation (RD) were calculated to determine the precision predictions from empirical equation used against the applied geotechnical data. An empirical relationship introduced by Motamed, Ghalandarzadeh, Tawhata & Tabatabaei (2007) has been selected in this study to predict the sediment thickness, H, which expressed in equation (2).

$$H \text{ (in meter)} = 135.19.\ F_o^{-1.9791} \quad (2)$$

3. Results and discussions

Squared average of HVSR curves at 28 measurement points in the study area has been computed, to determine the site fundamental frequencies. Overall, the distributions of significant peak fundamental frequencies are ranging from 2.05 Hz to 4.07 Hz (see Table 1) with only slight frequency differences between adjacent grid points. The fundamental resonant frequencies occurring at the maximum amplitudes are plotted into plane contour and space contour graphs as in Fig. 3. Gosar (2007) mentioned, it is widely accepted today that the frequency of HVSR peak reflects to the fundamental frequency of sediments, while the amplitude depends mainly on the impedance contrast with the bedrock and cannot be used as site amplification. As illustrated by the changes contour colours and elevations of F_o from Fig. 3, the distribution of sedimentary covers is expected diminishing significantly from East to West. The location of a new school building between lines B and C may be subjected to potential of resonance frequencies from 2.7 to 3.3 Hz where the building predominant frequencies should be avoided.

The changes of frequencies along the measurement lines indicate to the changes of soil stiffness and soil depth. This circumstance can be described by the general relationship of fundamental frequency, shear wave velocity, V_s, and sediment thickness as expressed in equation (3). From this equation, softer soil deposit (lower shear wave velocity, V_s) at deeper sediment thickness may influence to smaller frequency prediction and vice versa.

$$F_o \text{ (Hz)} = V_s / 4H \quad (3)$$

Calculation of sediment thicknesses from 2.05 to 4.07 Hz (or 0.25 to 0.49 sec, when the natural period is calculated inversely to natural frequency) according to equation (2) is tabulated in Table 1 indicates, the ground has been mostly dominated by dense or stiff classes as shaded in Table 2. Bigger frequency value may reflects to shallower depth estimation of soil deposit and at the same time the strength may also increases. Marek, Bray & Abrahamson (2009) summarized their study into Table 3, supports these calculated sediment thicknesses within 8.42 to 32.81 meters from 2.05 to 4.07 Hz of frequencies range as in the shaded row.

Further verification protocol was done through comparative borehole profile (see Fig. 4) of BH 1 and BH 2 as in Fig. 2, against the ambient vibration results closest to the boreholes locations. Single peak pattern of HVSR curves obtained from 562 and 597 measurement files (line B and C) by all sensors, S1', S2' and S3' in Fig. 5 which may described to the existence of big impedance contrast layer could be existed. The existence of soft layers described was strongly agreed when referring to the bore holes cross section as in Fig. 4. The cross section was classified from very soft to firm classes with the SPT 'N' profile almost vertically dropped to 15 meters depth from the ground surfaces. The soil strength was gradually developed when approaching BH 2 for additional 5 meters depth after exceeded 15 meters. Vice versa to the SPT 'N' profile of BH 1 when suddenly increased to 18 meters depth and reached to medium dense class. According to Kamarudin, Daud, Ibrahim, Z., Ibrahim, A, Yub & Mohd Noor (2014), a large velocity contrast can be described by a single sharp peak HVSR curve pattern, whereas the presence of multiple peaks with broader HVSR peak curve pattern can be due to the existence of multiple contrast layers presence. But sometimes, the peak spectrum might also be contaminated by the nearest structure response that should be careful evaluated. Details explanation on other type HVSR curve shape and its ground characterizations can be found in SESAME (2004).

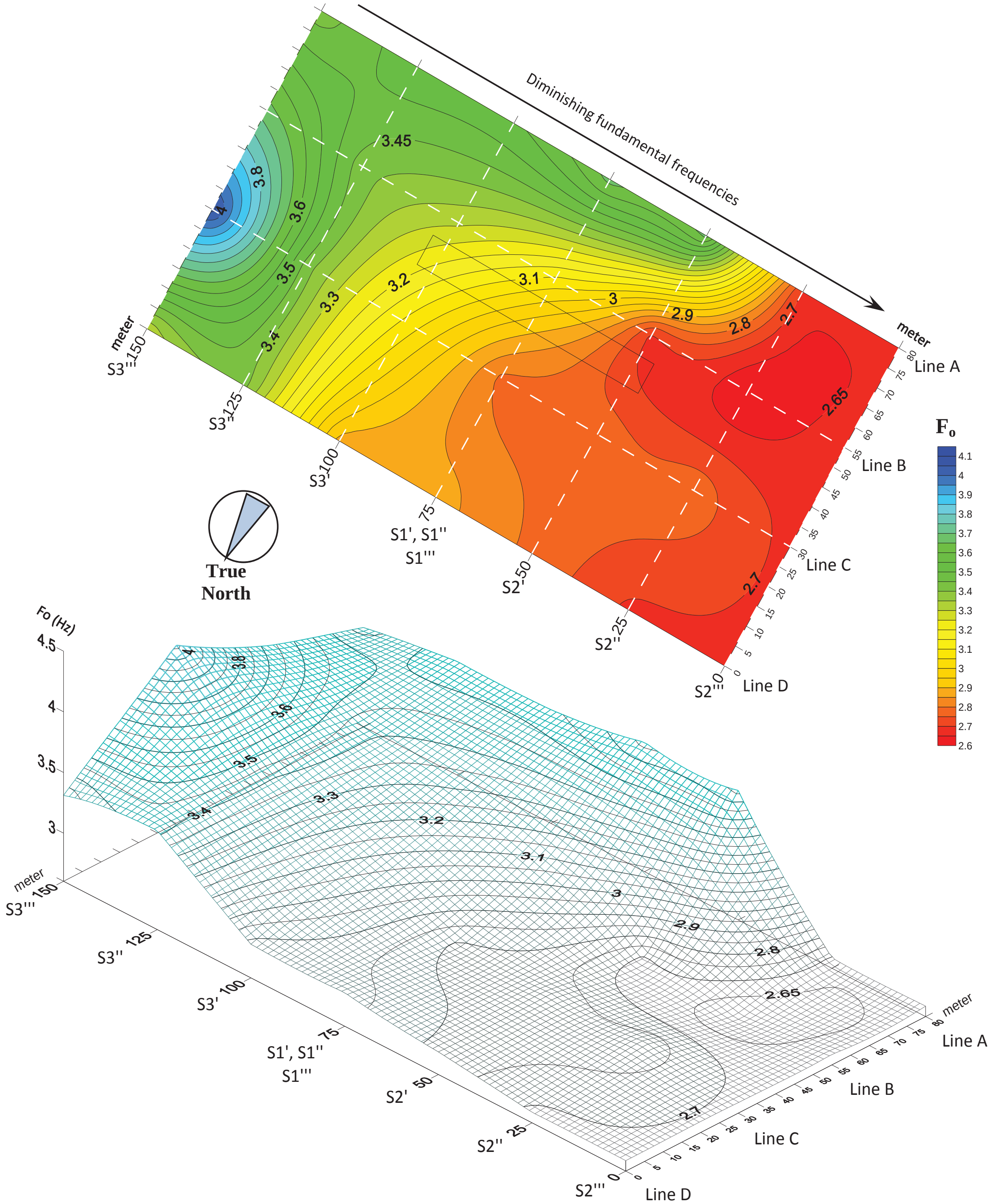

Fig. 3. Microzonation map of fundamental resonant frequencies from ambient vibration measurements in SK Sri Molek

Table 1. Details site fundamental frequency, F_o, site fundamental period, T_o, sediment thickness, H, for every measurement points

Stations and remarks	File and Sensor No.	No. of magnified peak	Event Date	F_o (Hz)	T_o (s)	Sedimentary cover estimation (meter)
Line A	602-S3'''	1 one)	23.12.2012	3.42	0.29	11.83
	603-S3''	1 (one)		3.42	0.29	11.83
	604-S3'	1 (one)		3.54	0.28	11.06
	602-S1'''	2 (two)		2.51	0.40	21.82
				3.80	0.26	9.65
	603-S1''	2 (two)		2.60	0.38	20.39
				3.67	0.27	10.33
	604-S1'	2 (two)		2.43	0.41	23.35
				3.54	0.28	11.06
				Average max peak curve spectral within S1 : 3.67	0.27	10.31
	604-S2'	2 (two)		2.60	0.38	20.39
				3.67	0.27	10.33
	603-S2''	1 (one)		2.69	0.37	19.05
	602-S2'''	1 (one)		2.69	0.37	19.05
Line B	601-S3'''	1 (one)	23.12.2012	3.67	0.27	10.33
	563-S3''	1 (one)		3.42	0.29	11.83
	562-S3'	1 (one)		3.31	0.30	12.67
	601-S1'''	1 (one)		2.98	0.34	15.53
	563-S1''	1 (one)		3.09	0.32	14.51
	562-S1'	1 (one)		2.98	0.34	15.53
				Average max peak curve spectral within S1 : 3.09	0.32	14.50
	562-S2'	1 (one)		2.69	0.37	19.05
	563-S2''	2 (two)		2.60	0.38	20.39
				3.20	0.31	13.56
	601-S2'''	1 (one)		2.69	0.37	19.05
Line C	600-S3'''	1 (one)	23.12.2012	4.07	0.25	8.42
	599-S3''	1 (one)		3.42	0.29	11.83
	597-S3'	1 (one)		3.09	0.32	14.51
	600-S1'''	1 (one)		2.79	0.36	17.79
	599-S1''	1 (one)		2.79	0.36	17.79
	597-S1'	1 (one)		2.88	0.35	16.62
				Average max peak curve spectral within S1 : 2.79	0.36	17.74
	597-S2'	1 (one)		2.79	0.36	17.79
	599-S2''	1 (one)		2.79	0.36	17.79
	600-S2'''	2 (two)		2.05	0.49	32.81
				2.69	0.37	19.05
Line D	576-S3'''	1 (one)	20.12.2012	3.31	0.30	12.67
	575-S3''	1 (one)		3.42	0.29	11.83
	573-S3'	1 (one)		2.88	0.35	16.62
	576-S1'''	1 (one)		2.88	0.35	16.62
	575-S1''	1 (one)		2.88	0.35	16.62
	573-S1'	1 (one)		2.88	0.35	16.62
				Average max peak curve spectral of S1 : 2.88	0.35	16.66
	573-S2'	1 (one)		2.79	0.36	17.79
	575-S2''	1 (one)		2.69	0.37	19.05
	576-S2'''	1 (one)		2.69	0.37	19.05

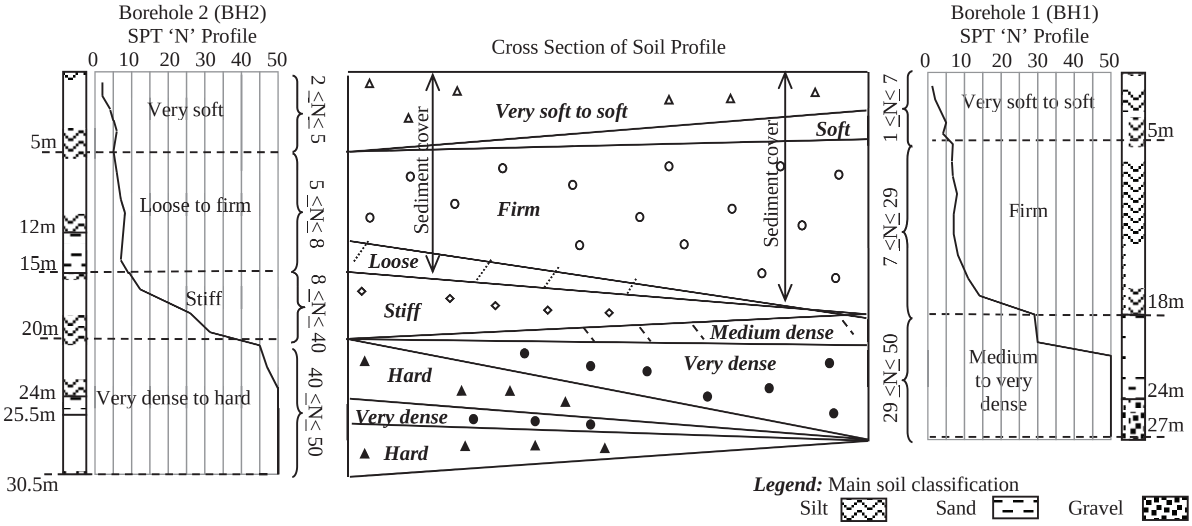

Fig. 4. SPT 'N' profile and boreholes cross section

Table 2. Ground classification for seismic design (Shinoda, Watanabe, Kojima & Tateyama, 2009)

Ground classification	Site period, T_o (s)	Description
G0	-	Hard rock
G1	-	Bedrock
G2	0.25 and shorter	Diluvium
G3	0.25 to 0.5	Dense soil
G4	0.5 to 0.75	Dense to soft soil
G5	0.75 to 1.0	Soft soil
G6	1.0 to 1.5	Very soft soil
G7	1.5 and longer	Extremely soft soil

Table 3. Simplified geotechnical site categories (Marek, Bray & Abrahamson, 2009)

Site A	Description	Site period, T_o	Comments
A	Hard rock	≤ 0.1 s	Hard, strong, intact rock : $V_s \geq 1{,}500$ m/s
B	Rock	≤ 0.2 s	Most "un-weathered" California rock cases ($V_s \geq$ 760 m/s or < 6 m of soil)
C-1	Weathered/ soft rock	≤ 0.4 s	Weather zone > 6 m and < 30 m (V_s > 360 m/s increasing to > 700 m/s)
-2	Shallow stiff soil	≤ 0.5 s	Soil depth > 6 m and < 30 m
-3	Intermediate depth stiff soil	≤ 0.8 s	Soil depth >30m and <60 m
D-1	Deep stiff holocene soil either S (sand) or C (clay)	≤ 1.4 s	Soil depth > 60 m and < 200 m. Sand has low fines content (<15 %) and plastic fines (PI > 5)
-2	Deep stiff pleistocene soil, S (sand) or C (clay)	≤ 0.4 s	Soil depth > 60 m and < 200 m. See D1 for S or C sub-categorization
-3	Very deep stiff soil	≤ 2 s	Soil depth > 200 m
E-1	Medium depth soft clay	≤ 0.7 s	Thickness of soft clay layer 3 m to 12 m
-2	Deep soft clay layer	≤ 1.4 s	Thickness of soft clay layer > 12 m
F	Special, e.g., potentially liquefiable sand or peat	~ 1 s	Holocene loose sand with high water table ($z_w \leq 6$ m) or organic peat.

By taking the datum at 15 meters (for BH 2) and 18 meters (for BH 1) depth, a comparison against the estimated sediment thicknesses has been made. Very small percentages of differences was achieved in this comparison (less than 5.81% excluding B: 562-S3’) as well as its relative deviation percentage (less than 9.41%) showed in Fig. 6 has proven to reliable F_o and equation (2) used in the prediction.

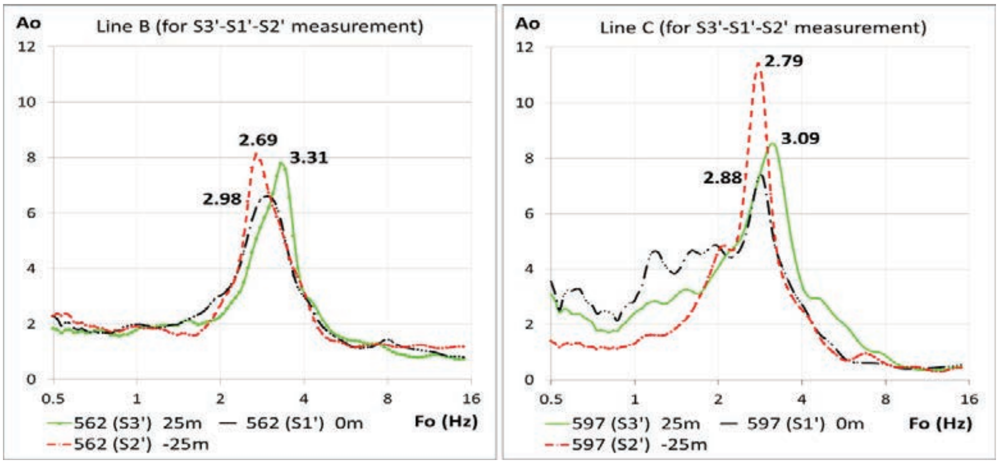

Fig. 5. HVSR curves pattern for measurement line B: S3’-S1’-S2’ (measurement file no. 562) and line C: S3’-S1’S2’ (measurement file no. 597)

Line B	Predicted Depth (m)	% of Differences
B: 562-S3'	12.67	15.56
B : 562-S1'	15.53	
B: 562-S2'	19.05	5.81

Line C	Predicted Depth (m)	% of Differences
C:597-S3'	14.51	3.26
C: 597-S1'	16.62	
C: 597-S2'	17.79	1.15

RD (%)	BH	Actual Depth (m)
9.41	BH2	15
2.33	BH1	18

Fig. 6. Difference percentage and relative deviation of sediment thickness between borehole depths against predicted soil depths

Increasing soil depth between sedimentary cover from BH 2 to BH 1 as labelled in Fig. 4, significantly coincide with computed H from ambient vibrations measurement files B: 562-S3’ & C: 597-S3’ to B: 562-S2’ & C: 597-S2’ as indicated in Fig. 7. In addition, ascending order showed by ambient vibrations measurement files B: 562-S1’ & C: 597-S1’, likewise match to the subsurface cross section envelope in between BH 2 and BH 1. In this scenario, ambient vibrations able to fill the middle gap cross section between both boreholes. F_o plays the vital role in filling the gap of sedimentary cover and agreed to Dinesh, Nair, Prasad, Nakkeeran & Radhakrishna (2010) when mentioned at the location where bore log data are not available, the bedrock profile can be mapped using the observed frequencies of HVSR peaks. It is also useful in this circumstance for a reference such as the frequencies contour or microzonation map as illustrated in Fig. 3, which also benefit to soil-structure resonance investigation as explained by Kamarudin, Daud, Ibrahim, Z., Ibrahim, A & Koh (2014).

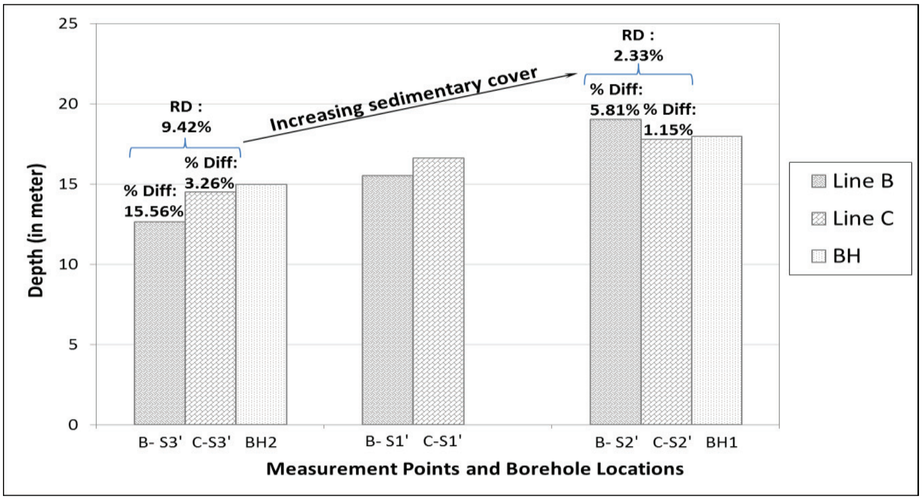

Fig. 7. Sediment thickness profile predicted empirically VS borehole depths

In last verification procedure according to Imai & Yoshimura (1970) relationship taken from Jafari, Shafiee & Razmkhah (2002), the proposed empirical formulation of Vs prediction for all type of soils can be estimated by using the expression as in equation (4) if the borelog data of SPT ‘N’ is available. By taking similar datum level at15 meters (SPT ‘N’ = 9) and 18 meters (SPT ‘N’ = 29) for the soil thickness or H, the computation of F_o from ambient vibrations according to equation (3) can be reviewed. F_o are found to be estimated at 2.61 Hz (for 15 meters datum) and 3.20 Hz (for 18 meters datum) significantly agreed to the peak fundamental frequencies of HVSR curves as in Fig. 5, which ranging from 2.69 Hz to 3.31 Hz. From this proven verification, the sedimentary cover can be visualized by shallower depth and stiffer layer at higher frequencies mostly found on the East, compared to the West part of the school compound from the microzonation map illustrated as given in Fig. 3.

$$V_s \text{ (m/s)} = 76.\ \text{SPT ‘N’}^{0.33} \tag{4}$$

From the processes of verification shown between ambient vibrations and geotechnical data performed, the application of ambient vibrations and HVSR method have proven reliable and easy to be adopted. In this study, sedimentary cover formation, soil thickness with its strength class can be estimated in quick with aided by some prove and reliable empirical formulations, typical soil classification tables from previous experiments and general relationship of $F_o = V_s/ 4H$.

Conclusions

Ambient vibrations measurement and HVSR method has been applied in low seismicity region of Peninsular Malaysia, specifically at primary school compound of SK Sri Molek by using seismometer instruments. From the findings, fundamental frequencies were obtained between 2.05 to 4.07 Hz that classified under shallow stiff or dense soil strength classification. Single peak sharp of HVSR curves most dominated in all measurement files may explain to the presence of one impedance soil contrast throughout the study area.

Very close verification agreement of site fundamental frequencies prediction, increased the ability and reliability of ambient vibrations and HVSR method predictions. By exploiting the characteristics of HVSR curves and F_o values, it shows that ambient vibrations is also sensitive in local soil characterization investigation, such as resonance frequency microzoning map, sedimentary cover estimation, strength classification and determination of potential number of subsurface layers. However, it is always being recommended to perform verification with minimum geotechnical data, with reliable empirical findings from previous studies to support the study being pursued.

Application of ambient vibrations technique and HVSR method has proven beneficial as an alternative method for wider picture of subsurface ground investigation due to cost-effective, non-destructive and also reliable. These sustainable features of ambient vibration technique might prompt and encourages effective monitoring or re-evaluation activities on existing assets especially to prevent from any unexpected threats against safety and loss.

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